



Nonlinear phenomenon in monocrystalline silicon based PV module for low power system: Lead acid battery for low energy storage



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ARTICLE INFO

Article history:

Received 10 March 2014

Received in revised form 29 June 2014

Accepted 1 July 2014

Available online 21 July 2014

Keywords:

Monocrystalline silicon

Photovoltaic module

Nonlinear

Indoor

Open circuit voltage

Short circuit current

Lead acid battery

Charge–discharge

Capacity

ABSTRACT

In the present work, we report the indoor photo-electrical measurements of monocrystalline silicon based photovoltaic (PV) module associated with 4 Ah lead acid battery as a storage unit for low power PV system applications. Concerning the PV module, our measurements show, at low illumination regime, that the short circuit current I_{SC} increases linearly with the illumination power levels. Moreover, for high illumination levels, the mechanism of bimolecular recombination and space charge limitation may be intensified and hence the short current of the PV module I_{SCMod} depends sub-linearly on the incident optical power; the behavior is nonlinear. For the open circuit voltage of the PV module V_{OCMod} measurements, a linear variation of the V_{OCMod} versus the short circuit current in semi-logarithmic scale has been noticed. The diode ideality factor n and diode saturation current I_s have been investigated; the values of n and I_s are approximately of 1.3 and 10^{-9} A, respectively. In addition, we have shown, for different discharging–charging currents rates (i.e. 0.35 A, 0.2 A and 0.04 A), that the battery voltage decreases with discharging time as well as discharging battery capacity, and on the other hand it increases with the charging time and will rise up until it maximized value. The initial result shows the possibility to use such lead acid battery for low power PV system, which is generally designed for the motorcycle battery.

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1. Introduction

The most photovoltaic PV modules are based on silicon (Si) as active semiconductor. Thus, different technologies are known, such as the crystalline (c-Si), the microcrystalline (μ -Si), the amorphous (a-Si) or the micromorphe (μ -a-Si) [1,2]. The main materials used for the PV modules encapsulation are in the polymer films form, with weak weights, such as the acrylic, the polyolefin and the Ethylene–vinyl acetate (EVA) [2]. The storage of the energy produced from the photovoltaic module is also important, and the development of photovoltaic technology implying that of the batteries. Also, the realization of the energy storage systems is of great interest for PV applications. Indeed, the lead-batteries remain the most commonly used batteries in particular for stand-alone photovoltaic systems, which the mainly function of batteries (i.e. lead acid) in photovoltaic systems is to provide power when the generating source is unavailable. The batteries are kept fully charged but immediately take up the load demand if the primary power source fails. These are designed for application such as serving as emergency power sources in uninterruptable power supplies. The battery development is related to the specific requirements of the photovoltaic mode of operation [3]. Thus, in order to control well the charging–discharging mechanism of the battery, a good design practice is needed to avoid the undesirable process like sulfating and freezing [4]. The most important characteristics of the battery for PV systems include the battery voltage and their capacity. Generally these parameters are related to the charging and discharging process, the life time of the battery, the maintenance of the battery and the efficiency. In addition, some PV systems may concern the mobile electronic devices: cell phones, laptops, sensors, panel displays, microprocessors, microcontroller and FPGA cards associated with low voltage (i.e. 4–5 V). In the present work, we focus our study on a critical nonlinear phenomenon of the electrical characteristics of monocrystalline photovoltaic module designed for low power PV system applications [5,6]. Thus, one of the originality of our work consists of the possibility to use such lead acid battery for PV system, which is generally designed to the motorcycle battery.

2. Experimental details

The PV source used in our study concerns a PV module (model: OY350-HELIOS) based on 20 silicon crystalline cells, which each 10 PV cells are connected between in series and in parallel with the 10 PV cells one (Fig. 1). The surface of the module is $S_{\text{Mod}} = 14\text{cm} \times 8\text{ cm}$. A Philips Lampe (PAR 38 EC FLOOD 30°, 230 V 120 W 6 A) has been chosen as the simulator light irradiation for the indoor current–voltage measurements of the PV module. A lux meter and power meter ($10^5\text{ lux} \approx 10^3\text{ W/m}^2$) have been used for measuring the irradiance. A lead battery (HT640, HUITONG BATTERY CO., LTD) with a nominal voltage of 6V and a capacity of 4Ah (10 h) was chosen in our study on battery performances. For the voltage–current I – V measurements, a Keithley 2000 multimeter as well as a digital compact ammeter and voltmeter have been used. Thus, a potentiometer as a rheostat (or variable resistor)

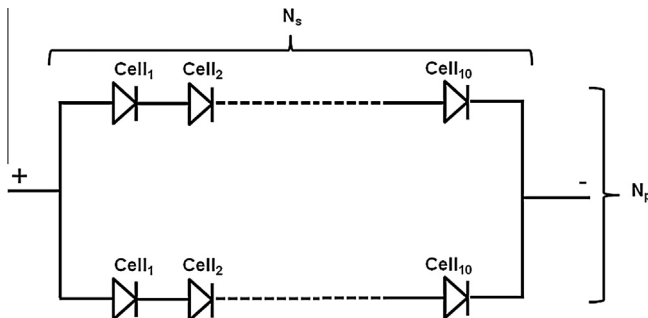


Fig. 1. PV module shown 10 cells connected between in series and in parallel with the 10 PV cells one ($N_s = 10$ and $N_p = 2$).

has been used for the I – V measurements. A thermometer HD8601P (100 Ω platinum RTD range: -50 $^{\circ}\text{C}$ to $+199$ $^{\circ}\text{C}$) was used for the temperature measurements. All the tests were carried out at room temperature and in open air.

3. Results and discussion

3.1. Photoelectrical model for photovoltaic module

The important use of the P – N junction diode is to convert the light energy to electrical energy as in the photovoltaic cell that can operate without any external power supply and relies on the optical power to generate the current and the voltage. The equivalent circuit of photovoltaic cell connected to the load R_L is presented in Fig. 2. The photoelectrical model of the photovoltaic cell includes a series resistance R_s and a shunt resistance R_{sh} ; R_s is the internal resistance of the cell, which depends on the semiconductor resistance, and R_{sh} is due to leakage at the junction. Thus, the current–voltage I – V characteristics of a PV cell are given by the following Eqs. (1) and (2):

$$I_C = I_{ph} - I_D - I_{sh} \quad (1)$$

$$I_C = I_{ph} - I_s \left(e^{\frac{q(V_C + R_s I_C)}{nkT}} - 1 \right) - \frac{V_C + R_s I_C}{R_{sh}} \quad (2)$$

where I_{ph} is the photocurrent, k the Boltzmann constant, q the elementary charge of electron, n the ideality factor of the junction, T is the temperature, and I_s the reverse saturation current of the diode that depends mainly on the temperature as well [7]:

$$I_s = AT^3 e^{\frac{-qE_g}{nkT}} \quad (3)$$

E_g and A represent respectively the band gap and constant with respect to temperature. Thus, the photogenerated current depends on the irradiation as well as the temperature [8]:

$$I_{ph} = \frac{G}{G_0} [I_{SC} + k_T(T - T_0)] \quad (4)$$

where $G_0 = 10^3 \text{ W/m}^2$ and $T_0 = 298 \text{ K}$ are the parameters obtained under the standard test conditions STC (AM 1.5, 25 $^{\circ}\text{C}$ and 10^3 W/m^2), and G , I_{SC} and k_T are the irradiation (in W/m^2), the short circuit current of the PV cell and the temperature coefficient (in A K^{-1}), respectively.

The photovoltaic module corresponds to a connected number of cells in series to increase the voltage or in parallel to increase the current. The equivalent circuit of a PV module connected to the load R_L (Fig. 3) can be deduced from that of one cell [8]. Thus, the current–voltage equation of PV module can be given by (Eq. (5)):

$$I_{Mod} = N_p I_C = N_p I_{ph} - N_p I_s \left(e^{\frac{q(V_{Mod} + R_s I_{Mod} \frac{N_s}{N_p})}{N_s nkT}} - 1 \right) - \frac{V_{Mod} \frac{N_p}{N_s} + R_s I_{Mod}}{R_{sh}} \quad (5)$$

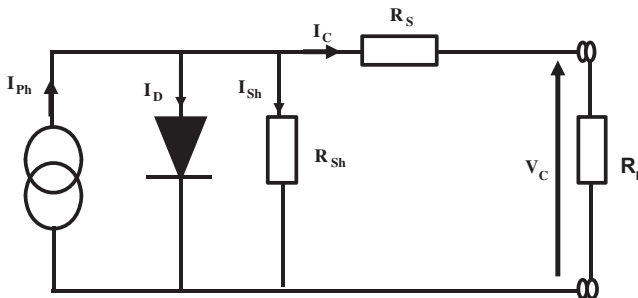


Fig. 2. Circuit of photovoltaic cell connected to the load R_L .

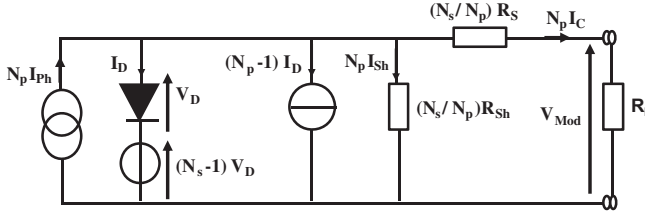


Fig. 3. Circuit of the PV module connected to the load R_L .

where N_s is the number of cells in series and N_p is the number of cells in parallel (i.e. Fig. 3; $N_s = 10$ and $N_p = 2$). In Fig. 4, we represent the short circuit current of PV module versus the light intensity in logarithmic scale. At low illumination intensities, we noticed that the current increase linearly with the light intensity. Moreover, for high light intensity levels a non linear behavior is noticed. For PN junction photovoltaic cell based PV module, the short circuit current of the PV module I_{SCMod} increases linearly with illumination level, and it correspond, in our case, to the total short circuit current for the number of cells in parallel N_p , which can be given by:

$$I_{SCMod} = N_p I_{SC} = N_p \frac{G_r \cdot P_{in}}{A_d} \quad (6)$$

where I_{SC} is the density short circuit current and A_d is the area of the diode, G_r and P_{in} are the generation rate and incident optical power [9]. Thus, for high levels of illumination, the mechanism of bimolecular recombination [10] and/or space charge limitation [11] may be intensified and hence the I_{SCMod} depends sublinearly on the P_{in} as:

$$I_{SCMod} = N_p \frac{G_r \cdot P_{in}^\alpha}{A_d} \quad (7)$$

where $\alpha < 1$, which is the exponent responsible for the non-linear effect that the photocurrent depends on. Similar behavior has been recently investigated in PV modules in other works [12].

In addition, the open circuit voltage of the PV module V_{OCMod} is related to the properties of the semiconductor; V_{OCMod} correspond to the total open circuit voltage for the number of cells in series N_s (i.e. $N_p I_C = 0$ and $V_{Mod} = V_{OCMod} = N_s V_{OC}$), where V_{OC} the open circuit voltage of the PV cell. Thus, V_{OCMod} may be expressed by the following formula:

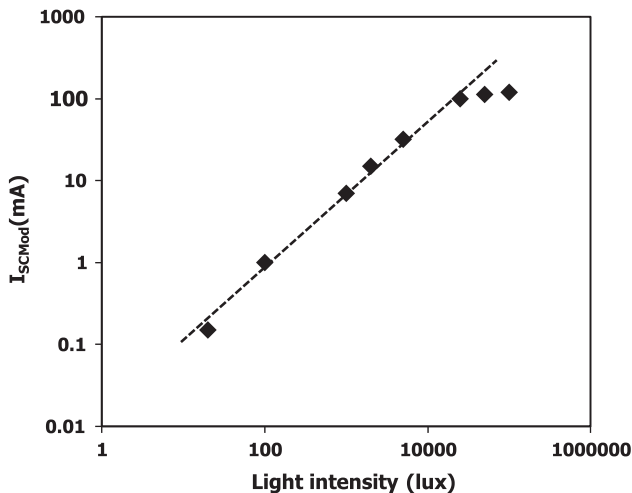


Fig. 4. Short circuit current of the PV module versus the light intensity (in logarithmic scale).

$$V_{OCMod} \approx N_s \frac{nkT}{q} \ln \left(\frac{I_{ph}}{I_s} + 1 \right) \quad (8)$$

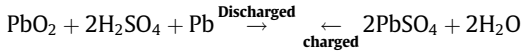
For normal illumination intensity levels, the photocurrent I_{ph} is approximately equal to the short circuit current I_{sc} , thus $I_{ph} \approx I_{sc} \approx I_{SCMod}/N_p$ may be considered, and consequently the V_{OCMod} can be expressed as [12]:

$$V_{OCMod} \approx N_s \frac{nkT}{q} \ln \left(\frac{I_{SCMod}}{N_p I_s} \right) \quad (9)$$

The open circuit voltage of the PV module versus the short circuit current in semi-logarithmic scale is shown in Fig. 5. From this plot and the Eq. (9), the diode ideality factor n of about 1.3 has been estimated, which it highly depends on the PV technology; generally it takes a value between 1 and 2 for silicon PV technology [7,13]. Thus, the diode saturation current I_s of about $\sim 10^{-9}$ A was obtained; it depends mainly as well as the diode ideality factor on temperature and irradiance [14,15]. In addition, we noticed for the high illumination levels, that the open circuit voltage of the PV module is relatively reduced. This behavior is may be attributed to the localized illumination, which may be related in inorganic PV to the large area dark diode connected in parallel to the small illuminated sub-cell [16].

3.2. Lead acid battery characteristics

The voltage battery is a key parameter for a battery and a standalone PV system, which is determined by the chemical processes in the battery, the concentrations and the polarization of the battery. The voltage calculated from equilibrium condition is known as the nominal voltage of the battery, which in practice cannot be readily measured, but for practical battery systems with low overvoltages and non ideal effects, the open circuit voltage is approximately the nominal battery voltage. The overall reactions in the battery cells are [17]:



The battery voltage is related to the current battery, and the internal series resistance of a battery (Eqs. (10) and (11)). The internal series resistance determines the maximum discharge current of the battery. Consequently, for applications in which the batteries are required to provide high instantaneous power, the internal series resistances should be low.

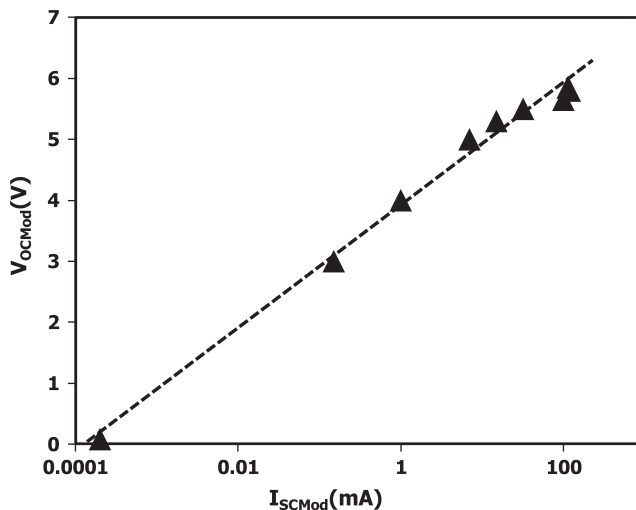


Fig. 5. Open circuit voltage of the PV module versus the short circuit current in semi-logarithmic scale.

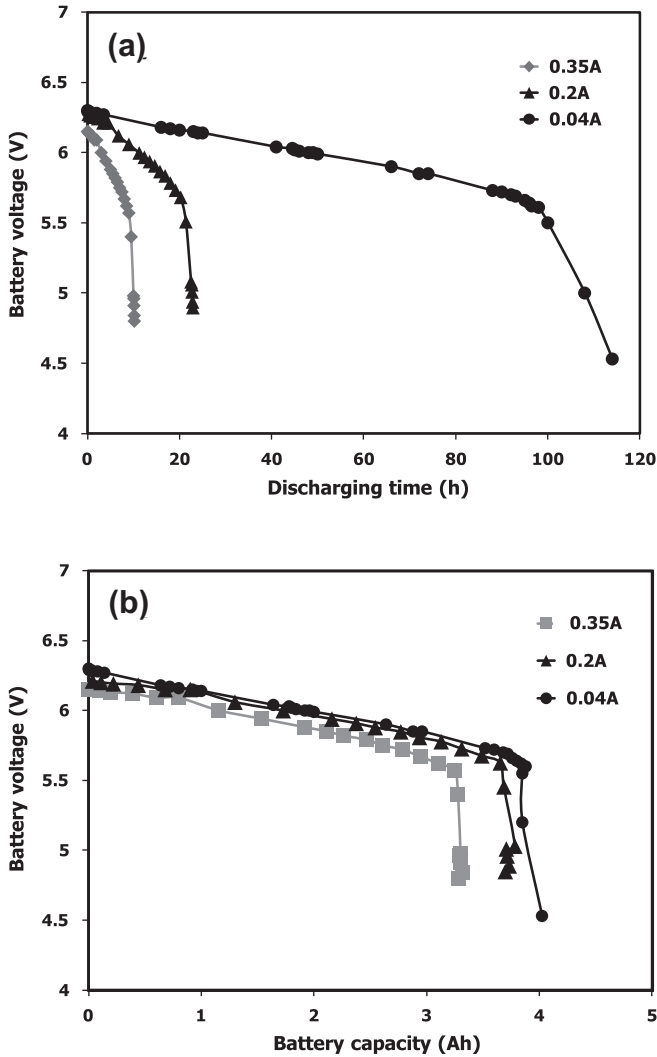


Fig. 6. (a) Battery voltage versus the discharging time at different discharge current rates. (b) Battery voltage versus the discharging battery capacity at different discharge current rates.

$$V = V_{OC} \pm rI \quad (10)$$

$$V_{OC} = A_0 d_e + B_0 \quad (11)$$

where d_e is the bulk density, A_0 and B_0 are constant.

In photovoltaic systems with battery, the charging mode with PV module is discontinuous, thus the charging from the battery is inevitable. The battery voltage discharging process of a lead battery at different discharging current rates are shown in Fig. 6a. The battery voltages are detected to be relatively linearly decreased until it reaches the over-discharge zone, where the battery voltage will decrease quickly owing to the nonlinear effects of electrochemical reactions in the battery [18,19]. The discharge curves (Fig. 6b) show that the discharging battery capacity is reduced when the battery is discharged at higher current of 0.35 A that correspond to the battery's rate capacity C_{10} . The discharged battery capacity is of about 3.25 Ah for the discharge current of 0.35 A, which remains higher with a

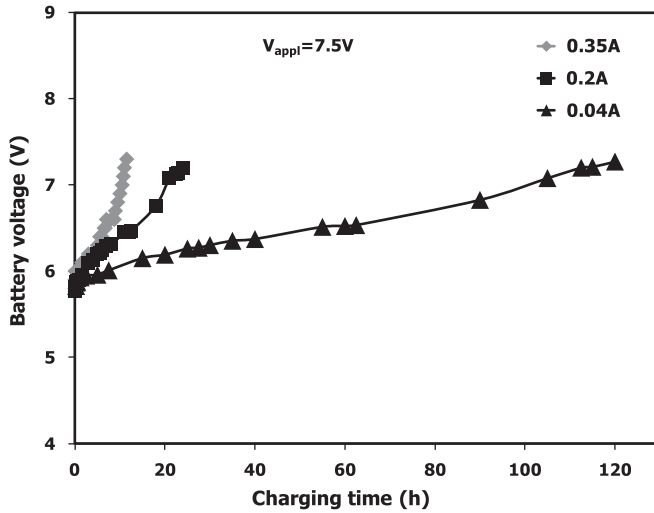


Fig. 7. Battery voltage versus the charging time at different charge current rates.

value of about 4 Ah for lower discharge current of 0.04 A (i.e. C_{100}). Moreover, the consumption of electro-active species in the battery, when it is connected to a load, causes the battery to reach a threshold known as the cutoff voltage. After reaching this voltage, the battery is considered to be discharged [20]. The further discharge will result in increasing the internal resistance of the battery and; consequently, in permanent damage of the battery [4,17,20,21]. Thus, further and deeply discharge operation may lead to sulphation of the negative electrode, which will cause failure of the battery [22,23]. However, the PV systems should be designed in accordance with the specific battery discharge capacity. The battery voltage versus the charging time of the lead acid battery for different charge current rates is presented in Fig. 7. The battery voltage will rise up until it maximized value where the battery cannot accept the energy any more [18,22,24]. The open circuit voltage after the load was disconnected gives an indication of the charge of the battery. The further charge as well as discharge will result in irreversible degradation of the battery [4,5,25,26].

4. Conclusions

In the present work, we reported the indoor electrical measurements of monocrystalline silicon based photovoltaic (PV) module and 4 Ah lead acid battery as a storage unit for low power PV systems, in particular for portable PV systems. We noticed for the PV module, at low illumination regime, that the short circuit current of the PV module I_{SCMod} increases linearly with illumination power levels. However, for high illumination levels, the mechanism of bimolecular recombination and space charge limitation may be intensified and hence the I_{SCMod} depends sublinearly on the incident power illumination. For the open circuit voltage of the PV module V_{OCMod} measurements, we have noticed a linear variation of the V_{OCMod} versus the short circuit current in semi-logarithmic scale. Thus, the diode ideality factor n and diode saturation current I_s values of about 1.3 and 10^{-9} A have been estimated, respectively. In addition, we have shown that the discharging battery capacity is reduced when the battery is discharged at higher current of 0.35 A that correspond to the rate capacity of the battery C_{10} ; the discharged battery capacity is about 3.25 Ah for the discharge current of 0.35 A, which remains higher of about 4 Ah for the lower discharge current of 0.04 A (i.e. C_{100}). Thus, the battery voltage increases with charging time and will rise up until it maximized value. This first result shows the possibility to use such lead acid battery, generally designed for the motorcycle battery, for original low power PV system.

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